


SM  $g/W/Z/\gamma$   


(Generalized) **Tri**-Boson  
(**Doubly**-**Resonant**) Signals from  
a Warped **Extra Dimension**  
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[Based on KA, Du, Hong, Sundrum (1608.00526): **theory**;  
KA, Collins, Du, Hong, Kim, Mishra (1612.00047, 1711.09920 and  
1809.07334): **LHC signals**]



# *“Disclaimer”*

- *General/schematic idea and summary of results only:  
details (plots etc.) in papers*
- *contact Peizhi Du ([peizhidu@gmail.com](mailto:peizhidu@gmail.com)) for model files*

**More details also in talk at Fermilab workshop (2019):**

**[https://indico.cern.ch/event/823181/contributions/3466225/attachments/1881783/3100810/  
multi\\_boson\\_FNAL.pdf](https://indico.cern.ch/event/823181/contributions/3466225/attachments/1881783/3100810/multi_boson_FNAL.pdf)**



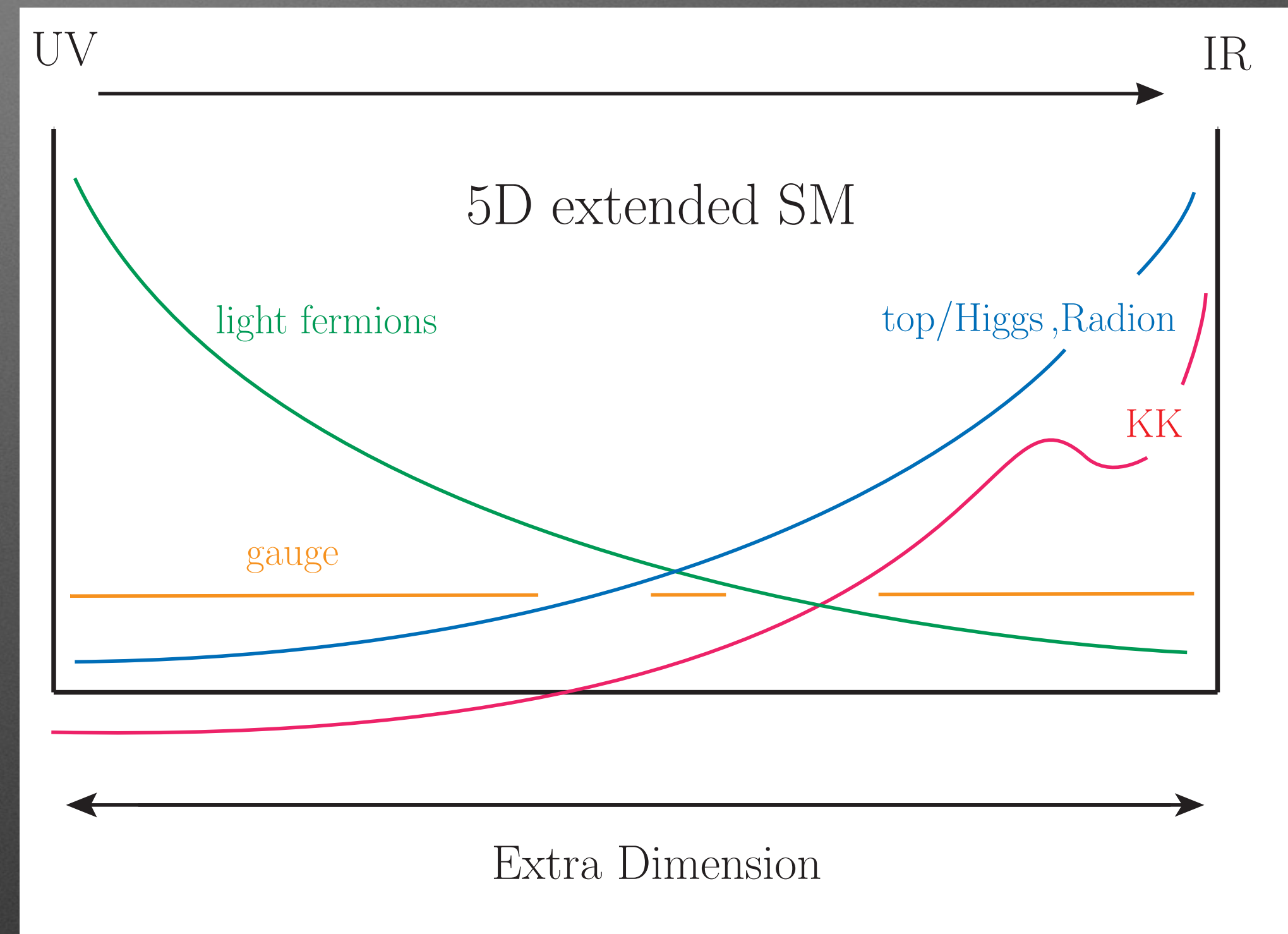
*Review of **standard** warped model*  
*[dual to **composite** Higgs (discuss **offline**): here*  
*use **geometrical** picture (easier to visualize)]*



# Standard warped model at a glance (everyone in same bulk, cf. later...)

- Planck-weak and flavor hierarchy problems (based on geometry/profiles)

- New particles: Kaluza-Klein (KK) excitations of SM (near TeV brane, along with top quark/Higgs, cf. light SM fermions near Planck brane)

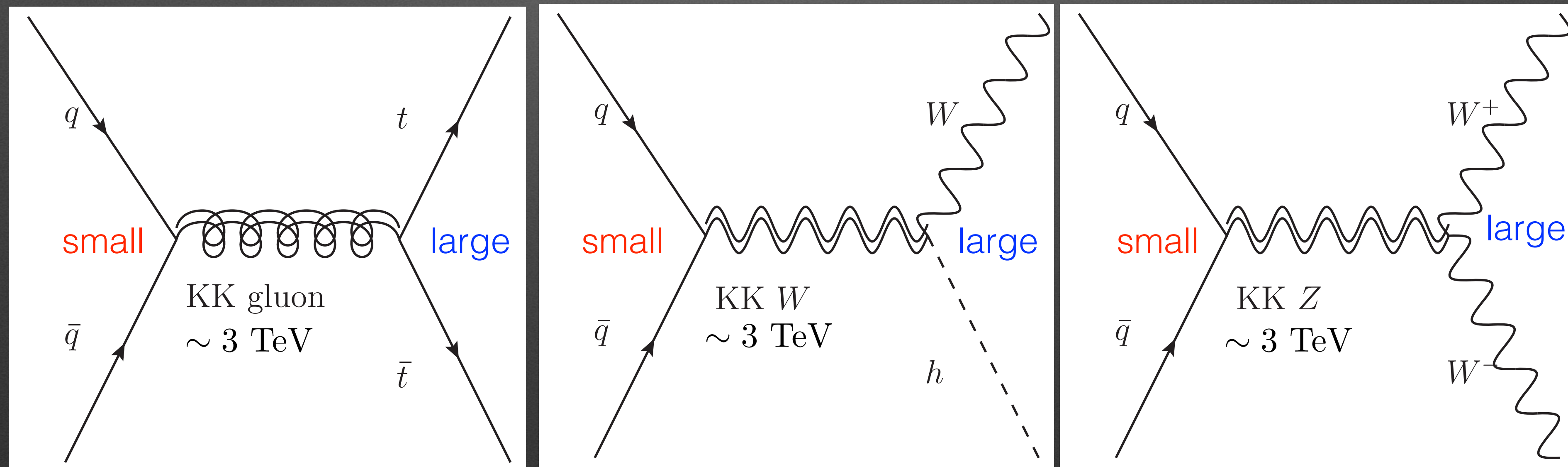


- Radion (fluctuation of size of extra dimension): also localized near TeV brane (like KK/top/Higgs), can be a bit lighter than gauge KK
- Two branes/endpoints



# LHC signals (assume a few TeV KK scale for this slide, using symmetries to satisfy precision tests)

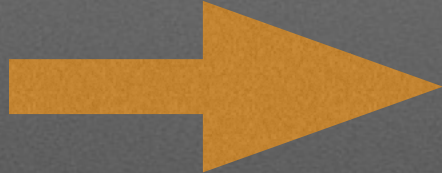
- focus on gauge KK signal [for a review, see Davoudiasl, Gopalakrishna, Ponton, Santiago (2009)]
- “nearest neighbor” effect: coupling in production via  $q\bar{q}$  small (one mode near TeV brane, other 2 near Planck brane); large for decay into pair of heavy SM,  $t\bar{t}$  (or  $W/Z_{\text{long.}}/h$ ) (all 3 modes near TeV brane) (cf. sequential  $W'/Z'$ : decay back into  $q\bar{q}$  or leptons)



- “classic” search for boosted top /  $W/Z_{\text{long.}}/h$ , using jet-substructure [for a review, see proceedings of “BOOST” workshops]



# What if we take flavor/CP bounds **at face value** (**no** symmetries)?!

- KK scale  $\sim O(10)$  TeV  no **on**-shell production at LHC?!  
(**in**direct signals still possible)
- ....maybe **not** (**rest** of this talk)!



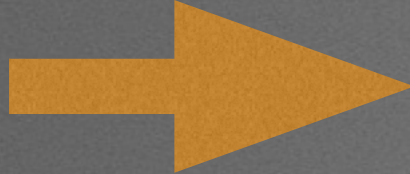
(...*end* of *review*, onto *new*...)

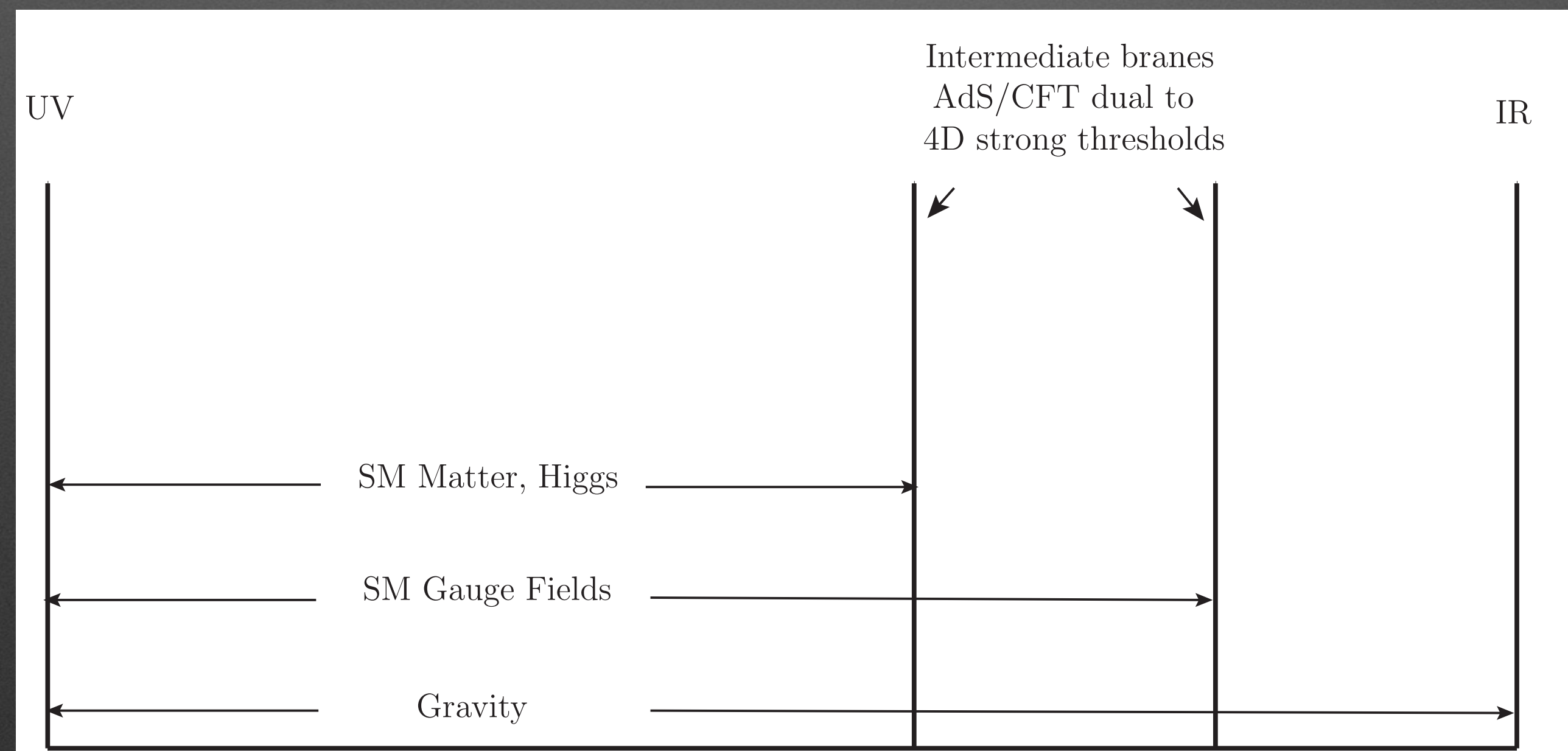
## *Simple extension(s)*

[KA, Du, Hong, Sundrum (2016)]



# General framework

- various fields in **different**, but overlapping “bulk” regions (plausible, reasonable)  **more** than **two** branes
- matter/Higgs till  $\sim O(10)$  TeV: satisfy flavor/CP
- gauge **continue** down to **a few** TeV (see later), gravity (possibly) even lower (another talk!)



- way to model **non**-trivial **IR** region (more structure than simply **one**, feature**less** brane)



*Treasure chest* (opens-up model/signal-  
building possibilities):

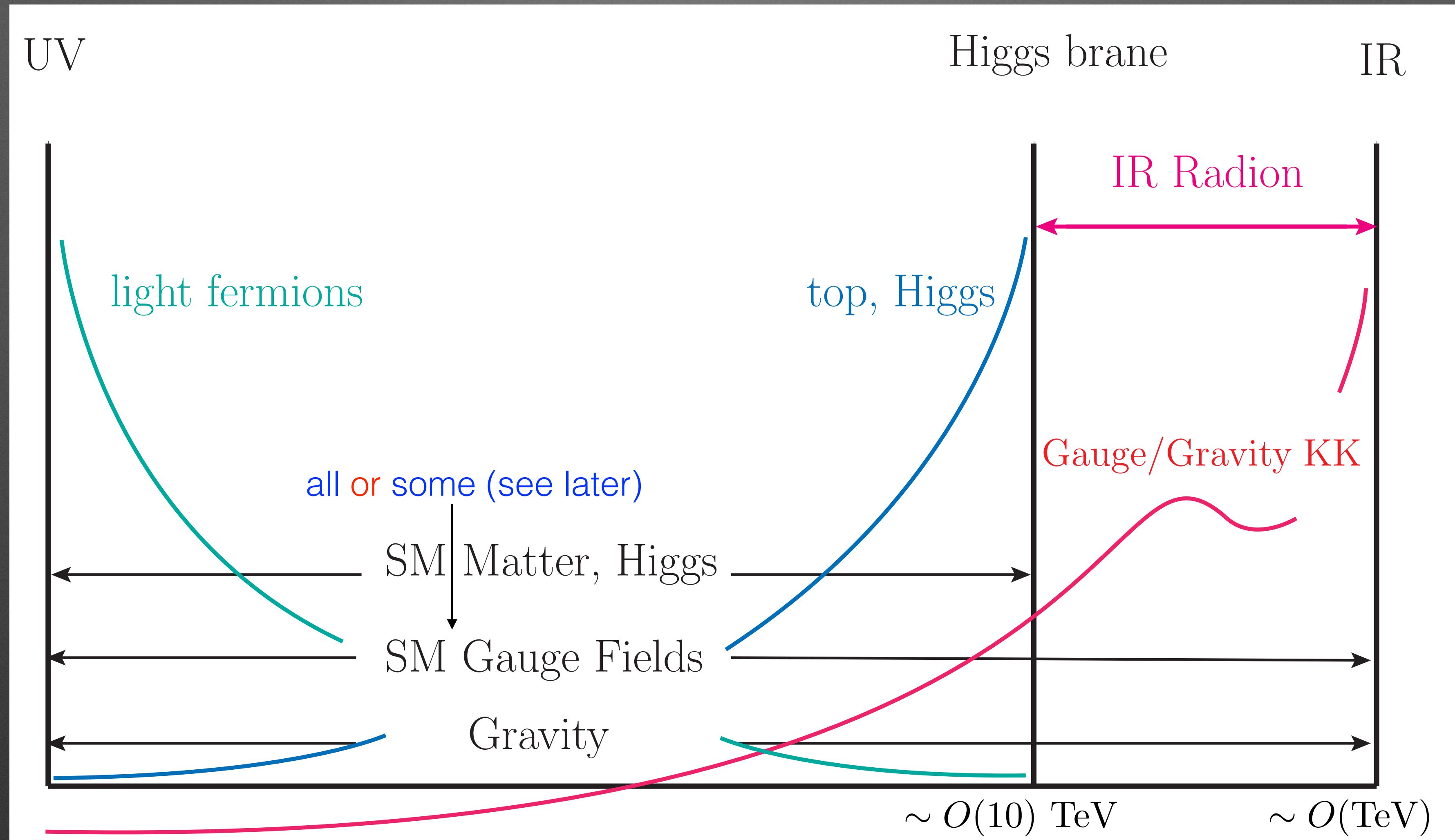
*focus* here on

*LHC* signals from *gauge KK* (as  
illustration + gives “*tri*-boson” signals):

*KK graviton* ( $\rightarrow$  4 gluons) in *other* EOI



# Extended warped model at a glance...



- **Gauge** fields in **entire** bulk (same as gravity) for **simplicity**
- (lightest) **gauge KK**, **radion** peak at (final) IR (**not** Higgs) brane

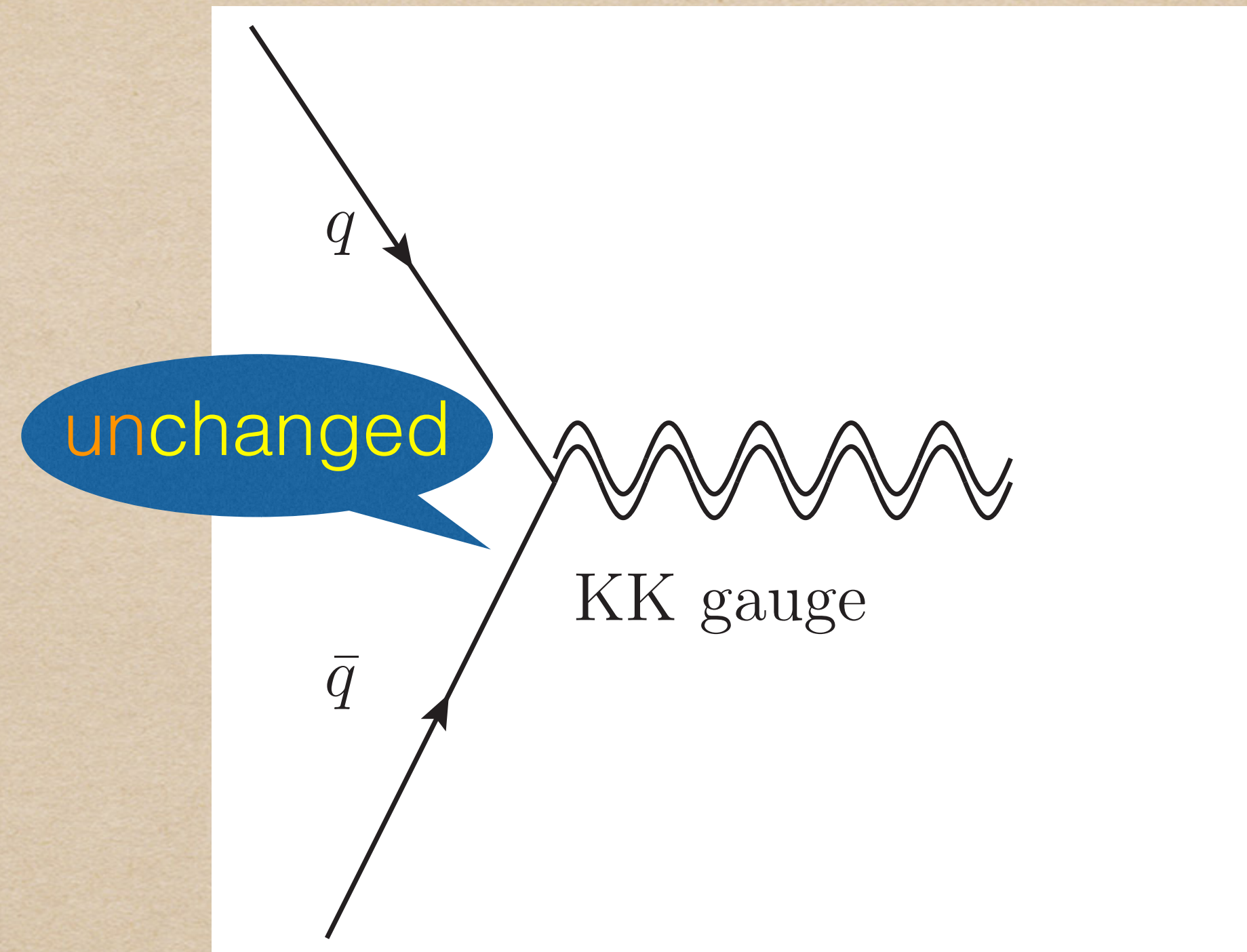


# New (lower) bound on gauge KK scale

- can show flavor/CP/EW precision (indirect) tests safe even for gauge KK  $\ll O(10)$  TeV (no symmetries), as long as matter/Higgs (most relevant for tests) till  $\sim O(10)$  TeV [like in standard (two branes) warped model]
- leading bound from direct search at LHC (see next)



# Production of gauge KK unchanged

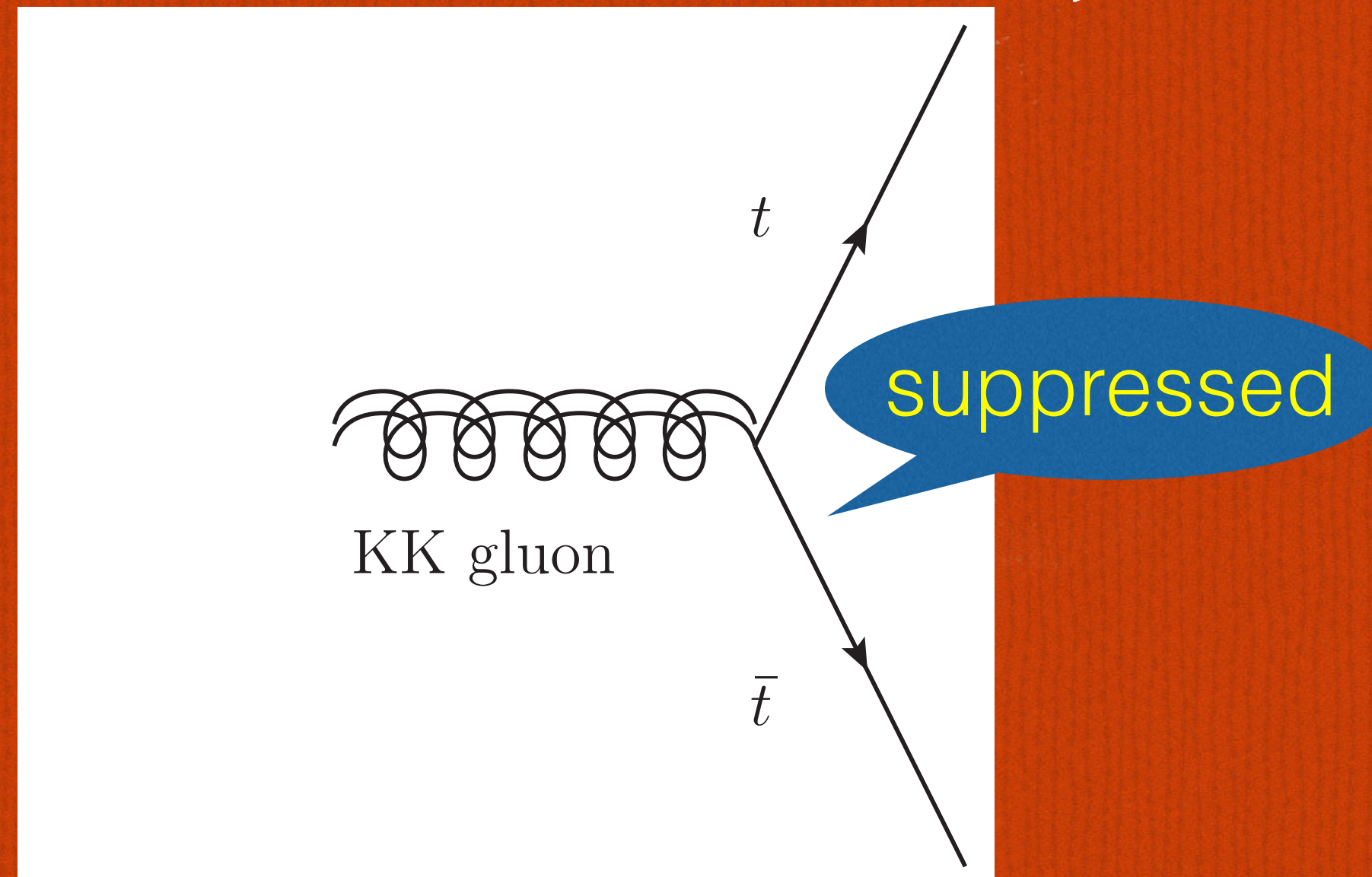


coupling  $\sim \frac{g_{\text{SM}}^2}{g_{\text{KK}}}$ , with  $3 \lesssim g_{\text{KK}} \lesssim 6$

- ◆ No modification near Planck brane (where  $q\bar{q}$  live)



Usual dominant decay modes of gauge KK [ $t\bar{t}$  (or  $W/Z_{\text{long.}}/h$ )]  
suppressed here (due to “sequestering”)



all 3 near  
TeV brane

coupling  $\sim g_{\text{KK}}$  (standard)  $\rightarrow \frac{g_{\text{SM}}^2}{g_{\text{KK}}}$  (extended), with  $3 \lesssim g_{\text{KK}} \lesssim 6$

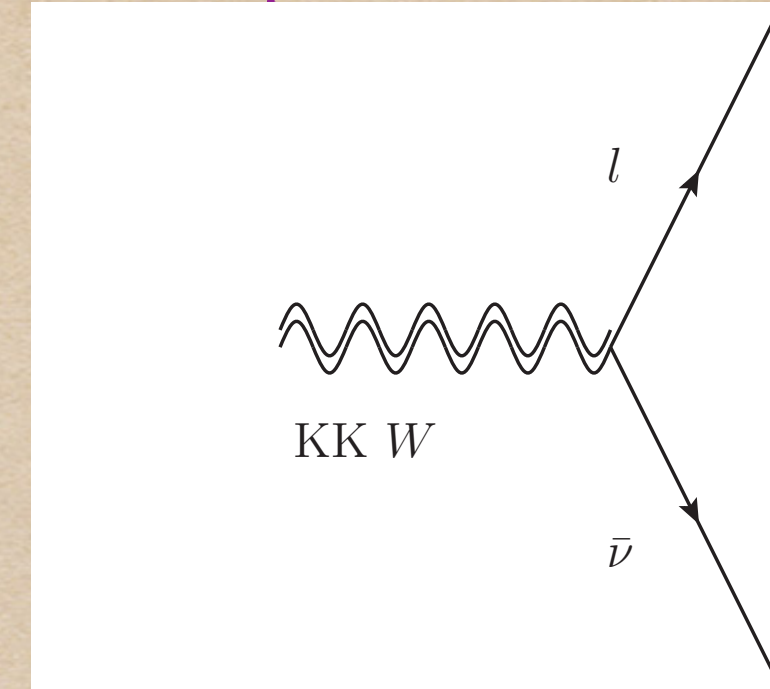
universal

- due to gauge KK “split” from top/Higgs

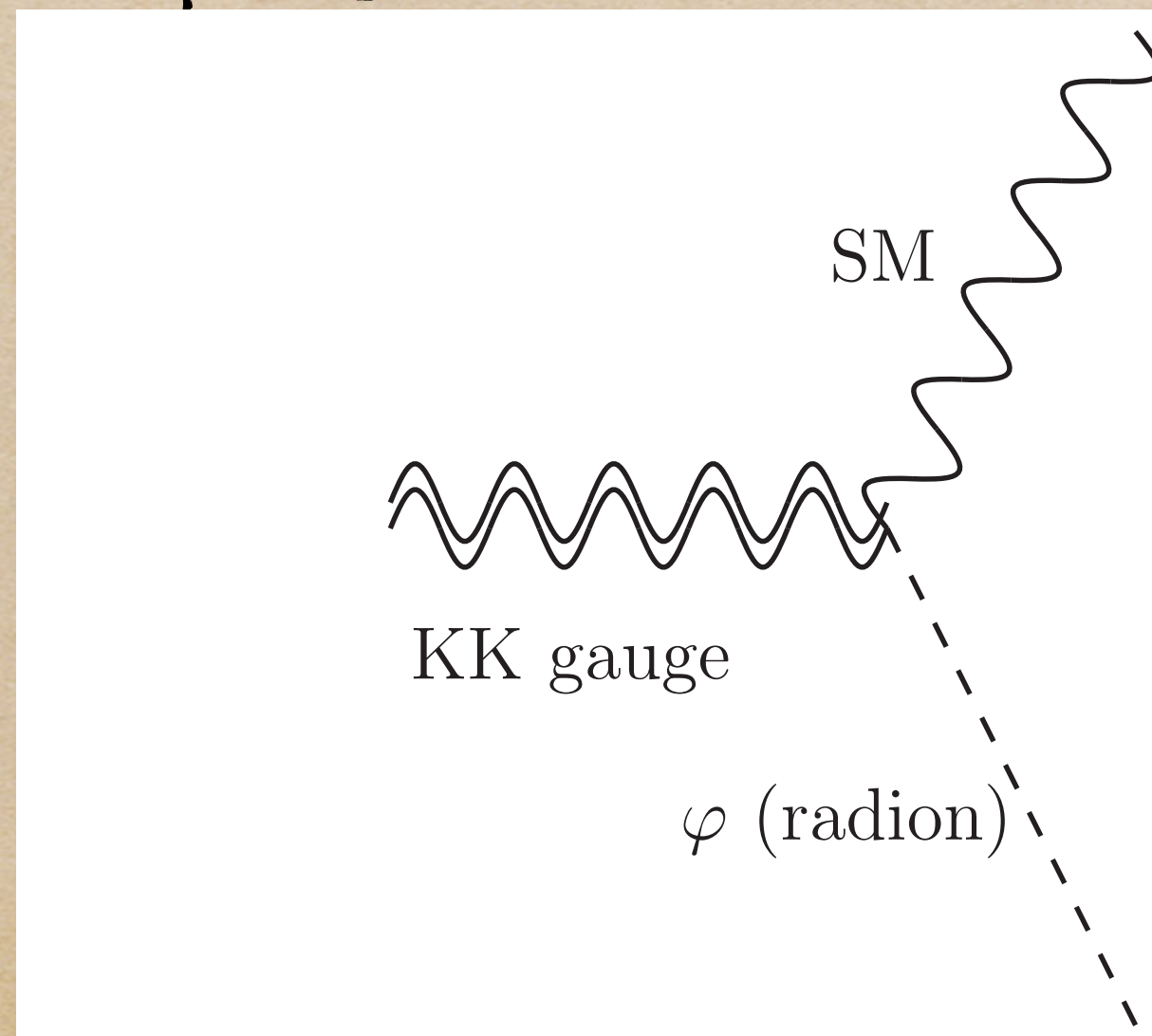


Other decay modes can then shine  
 [already existed with same strength, but were swamped earlier  
 (standard - 2 branes - model)]

- ◆ Gauge KK decay back into  $q\bar{q}$  (including  $t\bar{t}$ ) /  $l\nu$  gives bounds of a few TeV (likely discovery mode)



- ◆ Gauge KK decay into radion + SM gauge boson (focus of this talk):  
 coupling “in-between” to  $q\bar{q}$  and to  $t\bar{t}$  in standard case (2 branes)



$$\sim g_{\text{SM}} \epsilon \text{ (with } \epsilon \lesssim 1)$$

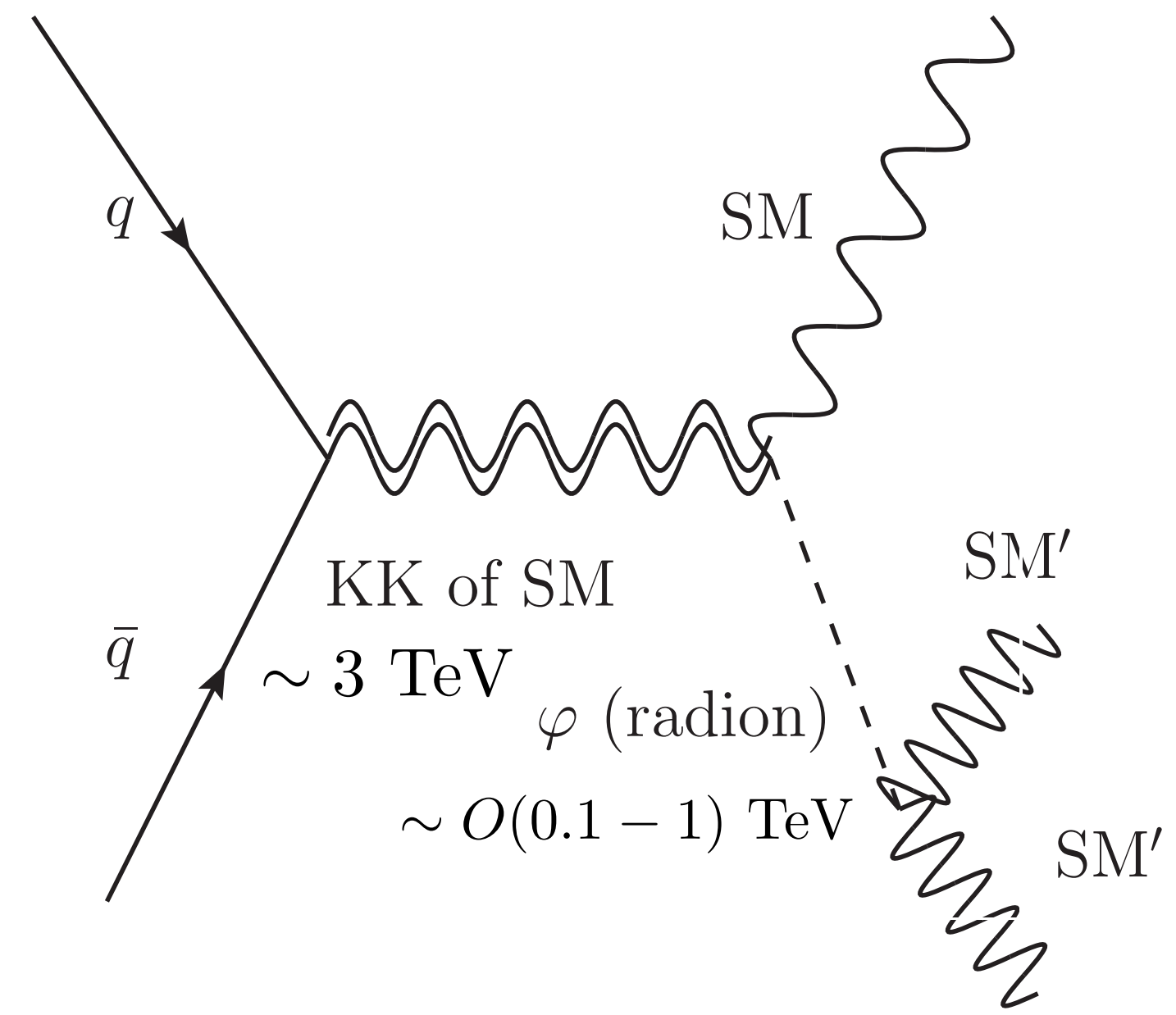
related to stabilization



“New” *cascade* decay channel (via *radion*) for *gauge KK* : *tri*-bosons of various kinds



Summary table/diagram (doubly-resonant, generalized “tri-boson”)



Signal features → (gauge KK $\sim 3 \text{ TeV}$ ) Radion mass ↓	General topology	Which gauge bosons <i>can</i> “play”?	(I). All SM gauge in extended bulk (1612.00047)	(II). Only EW in extended bulk (1711.09920 & 1809.07334)	(III). Only QCD in extended bulk (in progress)
Heavy ( $\gtrsim 1 \text{ TeV}$ )	Tri-boson, with 2 resonances: 2-particle (radion) & 3-particle (gauge KK)	gluons <i>and/or</i> EW	<i>Mixture</i> of gluons and EW gauge bosons (3 gluon/jet is largest)	<i>Mixture</i> of $W/Z/\gamma$ ( $WWW$ is largest): for $WWW$ etc., <i>combinatorics</i> makes <i>existing</i> di-boson search <i>inefficient</i>	<i>Only</i> 3 gluon/jet: <i>combinatorics</i> makes <i>existing</i> di-jet search <i>inefficient</i>
Light $O(100) \text{ GeV}$	isolated boson + <i>boosted/merged di-boson</i> resonance (radion) (combined resonance: gauge KK)	<i>Either</i> gluons <i>or</i> EW, i.e., <i>not</i> both	<i>not</i> possible	$W/Z/\gamma$ + <i>boosted/merged <math>WW/ZZ/Z\gamma/\gamma\gamma</math>:</i> search for 4-prong jet or lepton(s) inside 2-prong jet (for $WW/ZZ$ ); photon inside $Z$ -jet/leptons; allow $\Delta R_{\gamma\gamma} \lesssim 0.4$	gluon + <i>boosted/merged di-gluon:</i> <i>different</i> (in $N$ -subjettiness etc.) from $q\bar{q}$

- goldmine of “tri-boson” signals (+ 4 gluons from KK graviton in other EOI)!  
(Similar topology of signals possible with other new physics)